

Final Technical Report for NAG5-7284
**VERIFICATION AND IMPROVEMENT OF ERS-1/2 ALTIMETER
GEOPHYSICAL DATA RECORDS FOR GLOBAL CHANGE STUDIES**

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SUMMARY

This Final Technical Report summarizes the research work conducted under NASA's Physical Oceanography Program, Contract No. NAG5-7284, entitled, *Verification And Improvement Of ERS-1/2 Altimeter Geophysical Data Recorders For Global Change Studies*, for the time period from January 1, 2000 through June 30, 2000. This report also provides a summary of the investigation from July 1, 1997 – June 30, 2000. A web page illustrating some of the results of this investigation is on: <http://geodesy.eng.ohio-state.edu/ERS-Envisat/>.

The primary objectives of this investigation include verification and improvement of the ERS-1 and ERS-2 radar altimeter geophysical data records for distribution of the data to the ESA-approved U.S. ERS-1/2 investigators for global climate change studies. Specifically, the investigation is to verify and improve the ERS geophysical data record products by calibrating the instrument and assessing accuracy for the ERS-1/2 orbital, geophysical, media, and instrument corrections. The purpose is to ensure that the consistency of constants, standards and algorithms with TOPEX/POSEIDON radar altimeter for global climate change studies such as the monitoring and interpretation of long-term sea level change. This investigation has provided the current best precise orbits (<ftp://ftp.csr.utexas.edu/pub/ers1> and <ftp://ftp.csr.utexas.edu/pub/ers2>, with the radial orbit accuracy for ERS-1 (Phases C-G) and ERS-2 estimated at the 3-5 cm rms level, an 30-fold improvement compared to the 1993 accuracy. We have finalized the production and verification of the value-added ERS-1 mission (Phases A, B, C, D, E, F, and G), in collaboration with JPL PODAAC and the University of Texas. Orbit and data verification and improvement of algorithms led to the best data product available to-date. ERS-2 altimeter data have been improved and we have been active on Envisat (2001 launch) GDR algorithm review and improvement. The data improvement of ERS-1 and ERS-2 led to improvement in the global mean sea surface, marine gravity anomaly and bathymetry models, and a study of Antarctica mass balance, which was published in *Science* in 1998.

ERS-1 AND ERS-2 MISSION RADAR ALTIMETER DATA

We (B. Tapley, Coordinating Investigator of US WOCE PIs) have been supporting the ERS-1 and ERS-2 US data distributing effort. The previous mechanism for U.S. scientific

investigators to get free access to the ERS-1 and ERS-2 radar altimeter data is that the ESA/ESRIN data are sent through a designated Coordinating Investigator (CI), B. D. Tapley of University of Texas. The CI was to distribute data to ESA approved ERS-1/-2 investigators (the U.S. WOCE ERS investigators). The data distribution and archival center chosen is the JPL-PODAAC. The mechanism changed as of June 1998. ESA has released Announcements of Opportunities for ERS-2 again, and ESA's new mission, Envisat. For those who did not have an accepted proposal from ERS-2 and Envisat, they will not receive radar altimeter data. The PI of this investigation has submitted a proposal, entitled *Determination and Characterization of Long-Term Global Sea Level Change Using Satellite Radar Altimeters*, and requested for improved releases of ERS-1, ERS-2, and Envisat radar altimeter measurements to conduct sea level studies. The proposal has been accepted by ESA. The PI is also involved in one other Envisat proposals (see below), concerning the absolute calibration and sea level determination using Envisat, collaborating with the German colleagues at GFZ.

Under the PI's role as a member of the PODAAC User Working Group (UWG) playing an advisory role for PODAAC, the PI has been continuing to urged PODAAC initiate a discussion with ESA to request mission to freely distribute value-added ERS-1/-2 GDR to scientific investigators. The same concern goes for the availability of Envisat radar altimeter data. At present, ESA through Jerome Benenviste (ESRIN) has denied that we can distribute the value-added ERS-1 mission data product to scientific investigators, which are not approved by ESA.

Under the joint effort of the Ohio State University, JPL-PODAAC, and the University of Texas at Austin Center for Space Research (UTCSR), we have produced and help verified the value-added ERS-1 Mission (Phase A, B, C, D, E, F, and G). This data product is first such product to be produced. ESA/ESRIN's plan is to reprocess the ERS-1 data and release it earliest next year. The PODAAC GDR data are on DVD-ROMs can only now be released to the U.S. WOCE ESA-approved PIs. It is hope that ESA would eventually allow PODAAC to freely distributed to scientific investigators.

ERS PRECISE ORBIT PRODUCTION AND VERIFICATION

This investigation, through modeling and data improvement, has produced the most accurate ERS-1 and ERS-2 orbits today. The investigation is on collaboration with The production and verification of the ERS-1 and ERS-2 precise orbit generated using the TEG-3P gravity field model for most of the mission phases (Phases A, B, C, D, E, F and G) and for ERS-2 35-day repeat orbits were conducted jointly with the University of Texas Center for Space Research. The orbits were computed using satellite laser ranging (SLR) tracking data and altimeter crossover data for ERS-1 and PRARE and SLR tracking

data for ERS-2. Verifications and accuracy assessment indicate that these orbits (except Phases A and B for ERS-1) are accurate radially at the 3-5 cm rms level. However, the Phase A and B orbits are less accurate with radial errors at 10-25 cm rms, depending on tracking data coverage and quality of altimeter data. Comparison with other best available orbits, i.e., the orbits computed by Delft Technical University, indicates that the radial differences are consistently at the 3 cm rms level. The Delft orbit used a tailored JGM-3 gravity field model with ERS-1 crossover measurements, DGME04. Analysis using different gravity field models (JGM-3, TEG-3, TEG-3P, DGME04, EGM96) indicates that TEG-3P performs best in the SLR residual (global and at nadir to evaluate radial error), crossover residual, and in comparison with dynamic topographies computed using TOPEX/POSEIDON and using ERS-1. DGME04 is a close second. It is found that the dynamic tide modeling for the Delft orbit is based on a prelaunch T/P model and can therefore alias long period tidal errors due to K_1 and M_2 , at periods of one year and 92 days, respectively.

ERS-2 precise orbits have the benefit of precise and abundant tracking from the German PRARE system. Assessment of the Texas orbits indicates that the best orbits come from using both PRARE and SLR in three components, with the radial component accurate at the 3-4 cm rms level. There has been an effort at University of Texas to tune or improve the gravity field model using PRARE data. Results indicate that the improvement is substantial, the orbits (computed using the tuned gravity field model, TEG-3P) were being placed on the JPL-PODAAC value-added data product.

In summary, the effort conducted in this area produced a verifiable precise orbit for both ERS-1 and ERS-2 accurate radially at the 3-5 cm rms level, an almost 30 times improvement over the original ERS-1 orbit placed on the OPR02 in 1993 (which was accurate at the 1 m rms level).

ERS-1 AND ERS-2 ALTIMETER DATA PRODUCT IMPROVEMENT

The verification and improvement of the ERS-1 and ERS-2 OPR02 (versions 3.0 to 6.0) GDR released by ESA/ESRIN have produced to the most accurate and consistent (with TOPEX/POSEIDON data set) data products to-date. One reason to improve the data by computing more accurate and consistent corrections is because ESA's OPR02 data were released with different versions (3.0 to 6.0) and with distinct correction algorithms and even formats. The improved set of the ERS-1 data is ready for release to US investigators after the final verification at the OSU.

We have repaired data outages by providing ECMWF wet and dry corrections, notably in the coastal regions and near the poles. The latter problem in the original OPR02 data is

believed to be an algorithm error. 10 to 15% of the version 3 (in Phase C) data were recovered.

We have conducted a comparison of using IRI95 ionosphere model and the JPL GPS Ionosphere Map (GIM) to compute ERS-1 and ERS-2 ionosphere corrections, and in situ TOPEX dual-frequency ionosphere correction. Results indicate that for low to media solar activities and average over longer time span (days), IRI95 compares well with TOPEX ground truth and with GIM. An effort is initiated to work with the GPS groups (JPL and Bernie) to implement available GIM as ionosphere corrections for both ERS-1 and ERS-2.

We now understand the USO drift from ERS-1 and ERS-2, a correction with magnitudes around 1 cm/yr. The so-called SPTR data problems, which are caused by instruments resetting, are still not well understood. This problem has been especially bad for ERS-2.

Comparisons of ECMWF, TOPEX Microwave Radiometer (TMR), and ERS Microwave Radiometer (EMR) computed wet troposphere corrections, indicated differences of 7-8 mm rms, and offsets of 0.6-12 mm. TMR and EMR are biased at 12 mm, and ECMWF and TMR are biased only at 0.6 mm. The differences between TMR and EMR show geographical patterns, and the relative drift is at the 1.7 mm/yr level. An independent study at JPL by V. Zlotnicki comparing SSMI with TMR revealed algorithm problems for the TMR. V. Zlotnicki proposed a revised algorithm to the TMR at the Jason-1 meeting in Keystone, CO. Preliminary examination of this correction by comparisons with EMR indicates that V. Zlotnicki's revised algorithm is possibly in error, as the rms differences between the two radiometer corrections are notably larger (8.7 mm versus 7.2 mm rms) after the revised TMR corrections are applied [T. Urban, personal communication]. It is likely that TMR has a drift error on the order of 1.4 mm/yr, which goes directly into the sea level signal.

We have conducted sea level comparisons using WOCE tide gauges and using TOPEX sea level data. The comparisons indicated that sea level observed by 26 gauges and ERS-1 for 1.5 years (May 92 through January 94) has a difference at the 1.5 cm rms level; and around the value when ERS-1 sea level is compared with the TOPEX sea level during the same time period. The difference in sea level change trend is at the 0.6 mm/yr level with a formal uncertainty of 1.3 mm/yr.

We have undertaken an effort of the final verification for the JPL-PODAAC ERS-1 mission (beta) data product in addition to the extensive quality control procedures already conducted by JPL-PODAAC and UTCSR. A copy of the Verification Report is posted on the web page, <http://geodesy.eng.ohio-state.edu/ERS-Envisat>. The purpose is to ensure robustness of the data product. First, the data product generated by R. Berwin at

JPL has been compared with the data set independently computed by T. Urban at UTCSR. Second, WOCE island tide gauge data are used to verify phase-dependent bias estimates of different studies using a high-level sea level data derived from ERS-1 stackfile. T. Urban at UTCSR generated this stackfile. We provided JPL-PODAAC for a list of recommended changes to the data and to the edit criteria JPL-PODAAC had suggested. The web-site was built such that ERS-1 data users would be able to obtain the up-to-date information on the ERS-1 data product such as additional corrections and related software. The URL of this web site (<http://geodesy.eng.ohio-state.edu/ERS-Envisat/>) is linked from the JPL-PODAAC web site: http://podaac.jpl.nasa.gov/ers1_alt.

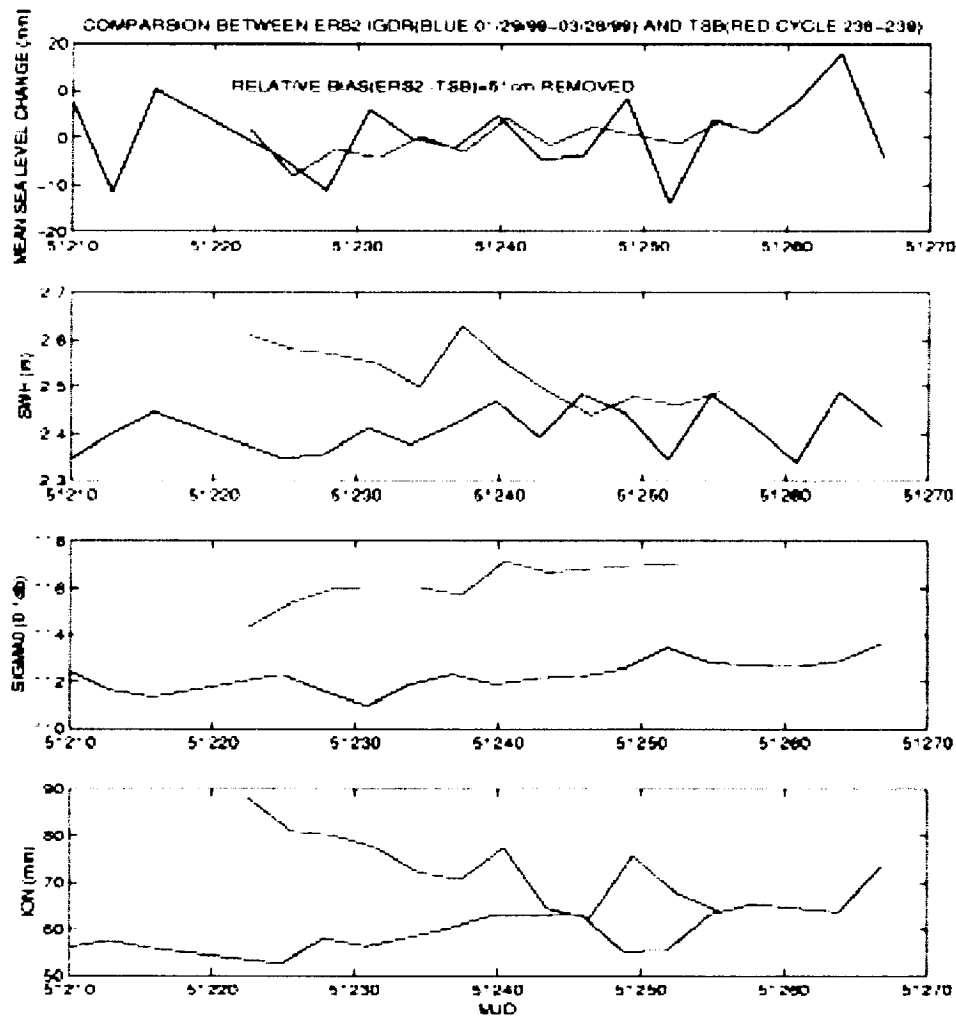
We have been conducting the Envisat RA GDR algorithm review as a member of ESA's Review Panel. We are currently building ERS-2 OPR02 database for a verification of geophysical and media corrections. This new ERS-2 database is based on ESA's OPR02 altimeter data and some corrections have been replaced with new improved ones such as GIM ionosphere correction of the University of Bern and sea state bias computed with Gaspar and Ogor's 1996 model parameters. In addition, the DPAF orbit was replaced with the UTCSR's TEG-3P precision orbit [Bordi, 1999]. This improved ERS-2 data and JPL's new ERS-1 GDR data product will be used in our studies of long-term sea level change and coastal tide modeling.

APPROVED ENVISAT PROPOSALS

ESA has approved the following relevant proposals which were responded to the Envisat announcement of Opportunity (data proposals):

Determination and Characterization of Long-Term Global Sea Level Change Using Satellite Radar Altimeters, 1999-2004, European Space Agency, PI: **C.K. Shum**, Co-Is: Chris Jekeli and Michael Parke, Ohio State University, USA; Stephane Calmant, ORSTOM de Noumea, New Caledonia; Gunter Hein, IfEN, Wolfgang Bosch, DGFI, and Reinhard Dietrich, TU Dresden, Germany; Roberto Guitierrez and Bob Schutz, UT/CSR, USA; Bruce Haines and Gerard Kruizinga, JPL, USA; A. Ruis, IEEC/CSIC, J. Martinez-Benjamin, IEEC/UPC, J. Font, ICM/CSIC, Marc Garcia, LIM/UPC, Spain; Neil White, John Church, CSIRO Marine Research and Antarctic CRC, Richard Coleman, University of Tasmania and CSIRO Marine Research, and Wolfgang Scherer, NTF/Flinders Univ., Australia (Data Proposal).

Combined Absolute And Relative Calibration Of Envisat RA-2, ERS-2, And Other Altimeters By GPS Equipped Buoys, ESA ENVISAT, PI: **G. Hein**, Co-PI: C. K. Shum et al., Dec. 1998 (Data Proposal).



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Fig. 1. Global Comparison of ERS-2 Altimeter with TOPEX Side B Altimeter.

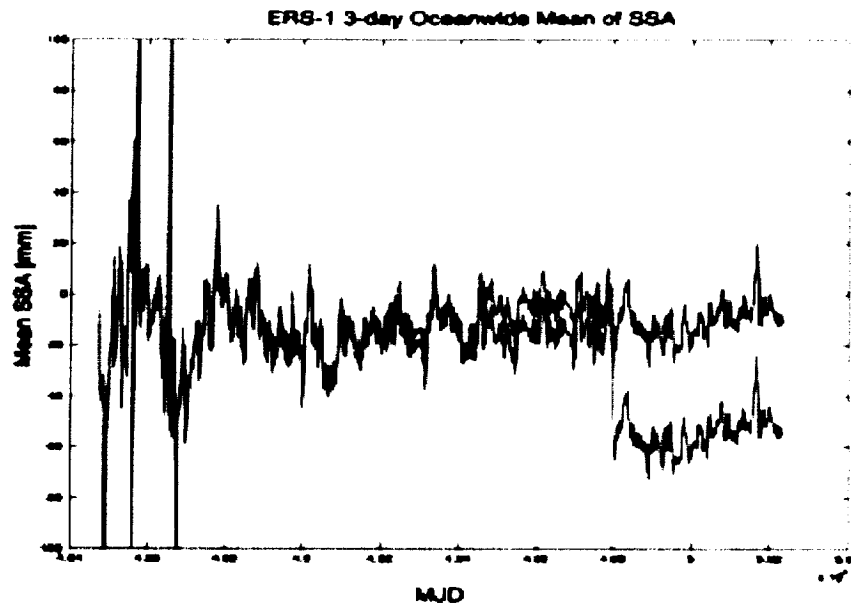


Fig. 2. Mean sea level implied by the JPL-PODAAC ERS-1 beta data product. Blue line represents the sea level applied with Shum et al. [1999b] biases, and the red line is the sea level with the Ries et al. biases [1999] applied.

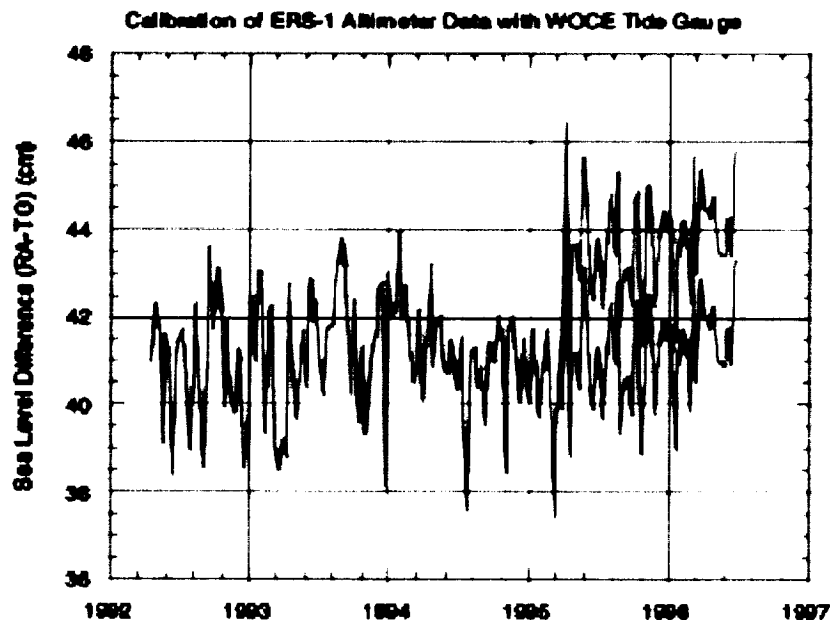
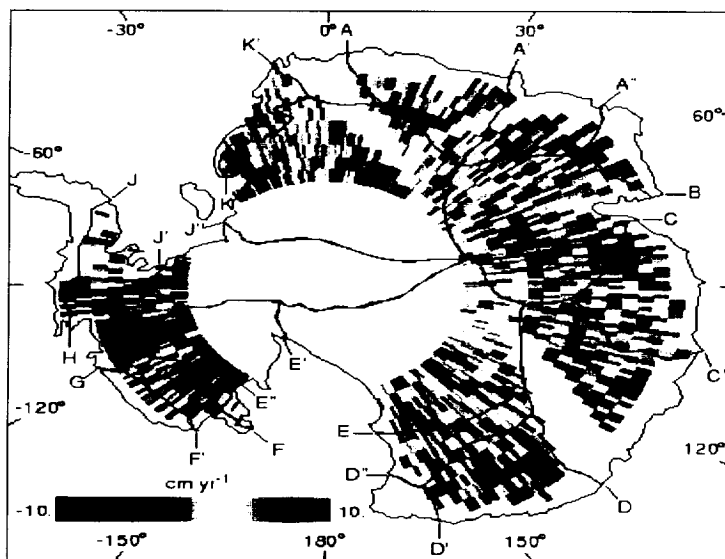


Fig. 3. Sea level differences between ERS-1(version 1.2 through 6 data products) radar altimeter (RA) and WOCE tide gauges (TG). The blue line represents the differences using the Shum et al. [1999b] biases; the red line is the sea level differences with the Ries et al. biases [1999] applied. 43 of 53 WOCE island tide gauges were used.

ANTARCTICA ICE SHEET MASS BALANCE



The change in elevation from 1992 to 1996 (expressed in cm yr^{-1}) of 63% of the grounded Antarctic Ice Sheet at a resolution of 1° by 1° , determined from ERS satellite altimeter measurements. (Wingham, D., A. Ridout, R. Scharroo, R. Arthern, and C. Shum, Science, 1998)



Fig. 4. Antarctica interior elevation changes from 1992-1996.

The improved ERS-1 and ERS-2 media and geophysical corrections were used to improve the over ice data which have to be retracked in a collaboration with University College London. Fig. 4 shows that a geographical plot of the ice elevation change (corrected for accumulation) which infers "ice thickness change" from 1992-1996, which indicated that interior ice sheet of Antarctica has an almost zero mass balance [Wingham et al., 1998].

GLOBAL MEAN SEA SURFACE, GRAVITY ANOMALY AND BATHYMETRY MODELS

The improved ERS-1 data, in particular the Geodetic Phase (183-day interleave orbits) data, have been used to significantly improve the global mean sea surface, marine gravity anomaly, and bathymetry models, conducted in part under this investigation and also benefited other similar research. The Geodetic Phase data release in part also resulted in the declassification of the Geosat Geodetic Mission (GM) data.

RELEVANT PRESENTATIONS AND PUBLICATIONS

A list of presentations and publications relevant to the investigation is provided as follows.

- Anzenhofer, M., A. Braun, M. Rentsch, C. Reigber, and C. Shum, Coastal Altimetry and Application, EGS, The Hague, Netherlands, April 1999.
- Berwin, R. W., ERS-1 altimeter value-added GDR user's reference manual, JPL-PODAAC, 1999.
- Bordi, J., The precise range and range-rate equipment (PRARE) and its application to precise orbit determination, PhD dissertation, The University of Texas at Austin, May 1999.
- Bordi, J., J. Ries, and B. Tapley, Analysis of PRARE and its application to precise orbit determination, EGS XXIII General Assembly, Nice, France, April 20-24, 1998.
- Kruizinga, G., Validation and applications of satellite radar altimetry, PhD Dissertation, Center for Space Research, University of Texas at Austin, December, 1997.
- Nuth, V., C. R. Wilson, M. K. Cheng, C. K. Shum, The application of radar altimeter to the problem of ice sheet thickness changes, Geophysical Research Abstracts, Vol. 1, No. 1, pp. 217, EGS 24th General Assembly, The Hague, The Netherlands, 1999.
- Nuth, V., C. Wilson, J. Chen, D. Blankenship, B. Schutz, C. Shum and B. Tapley, Seasonal change of ice sheet thickness from ERS-1 radar altimeter, in review, J. of Geodesy, 2000.

- Ries, J. C., J. J. Bordi, T. J. Urban, Precise orbits for ERS-1 using laser ranging and altimeter crossovers, CSR, University of Texas at Austin, CSR-TM-99-02, March, 1999.
- Seago, J.H., Orbital Accuracy and Quality Assessment Techniques for the ERS-1 Altimetric Satellite, CSR Technical Memorandum CSR-TM-97-06, 1997.
- Shum, C., J. Ries, J. Bordi, J. Seago, B. Tapley, and T. Urban, ERS-1/-2 precision orbit determination and accuracy verification, *Proc. Second ERS Symposium*, Florence, Italy, March 18-21, 1997.
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- Shum, C. K., Y. Yi, C. Zhao, T. J. Urban, and J. C. Ries, Value-added ERS-1 mission radar altimeter data product, Data Verification Report, September, 1999.
- Shum, C.K., Review of the Envisat RA2 algorithm, Envisat RA-2/MWR Algorithm Workshop, ESA/ESRIN, Frascati, Italy, June 8-9, 1999.
- Shum, C., M. Parke, Y. Yi, C. Zhao, K. Cheng, H. Tseng, M. Anzenhofer, C. Reigber, J. Benjamin-Martinez, J. Blaha, R. Dietrich, G. Liebsch, K. Novotny, G. Kruizinga, C. Morris, R. Francis, D. Martin, G. Mader, and T. Urban, Absolute altimeter calibration and validation of multiple radar altimeters, invited presentation, GLOSS Sea Level Workshop, GRGS, Toulouse, France, May 1999.
- Shum, C., C. Huang, D. Martin, M. Parke, W. Scherer, P. Woodworth, Combining GPS, tide gauge and radar altimetry in the determination of mean sea level variations, GPS99 meeting, Tsukuba, Japan, October, 1999.
- Shum, C., Envisat RA2 Algorithm Review Meeting, ESA/ESRIN, Frascati, Italy, June, 1999.
- Shum, C, H. Tseng, C. Zhao, T. Urban, B. Tapley, M. Anzenhofer, and P. Woodworth, Determination and characterization of long-term mean sea level change, IUGG Symposia, JS11, Birmingham, UK, July, 1999.
- Shum, C., C. Zhao, and P. Woodworth, Determination and characterization of global mean sea level change, EGS' First Vening Meinesz Conference on "Global and Regional Sea-Level Changes and the Hydrological Cycle", Loiri-Porto San Paolo, Sardinia, Italy, October 4-7, 1999.
- Shum, C., C. Zhao, Y. Yi, C. Reigber, A. Braun, T. Schoene, D. Wolf, and P. Woodworth, Determination and characterization of global mean sea level change, ERS-ENVISAT Symposium, Gothenburg, Sweden, October 2000.
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